Opto-mechanical integration and alignment verification of the James Webb Space Telescope (JWST) Optical Telescope Element

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ABSTRACT

The Optical Telescope Element (OTE) consists of a 6.6 m, all-reflective, three-mirror anastigmat. The 18-segment primary mirror (PM) presents unique and challenging assembly, integration and alignment requirements. To integrate and verify each of the Primary Mirror Segment Assemblies (PMSAs), an integrated network of laser trackers will be used in the Ambient Optical Assembly Stand (AOAS). The AOAS consists of an optical bench (OB) to support the JWST Optical Telescope Element (OTE), a personnel access platform structure (PAPS), an optics integration gantry system (OIGS), and a PMSA alignment and integration fixture (PAIF). The PAIF and OIGS are used to deliver, offload and precision align each PMSA segment and the aft optical subsystem (AOS) to their integration locations. This paper will introduce the functional design of this ground support equipment (GSE), illustrate the coordinate systems used for integration, and detail the integration processes.

Keywords: James Webb Space Telescope, JWST, mirror integration

1. INTRODUCTION

The James Webb Space Telescope program is directed by NASA Goddard Space Flight Center (GSFC) through the prime contractor, Northrop Grumman Aerospace Systems (NGAS). The James Webb Space Telescope consists of 3 primary elements: The Optical Telescope Element (OTE), the Integrated Science Instruments Module (ISIM), and the spacecraft element. The OTE optical design consists of a primary mirror comprised of 18 hexagonal mirror segment assemblies (PMSAs), a secondary mirror assembly (SMA) and an aft optic subsystem (AOS) as detailed in Figure 2 and Figure 3. The primary and secondary mirror segments are adjusted in 6 degrees of freedom by means of 6 hexapod actuators per assembly and the primary mirror segments also have radius of curvature control. All mirrors are made of Beryllium.

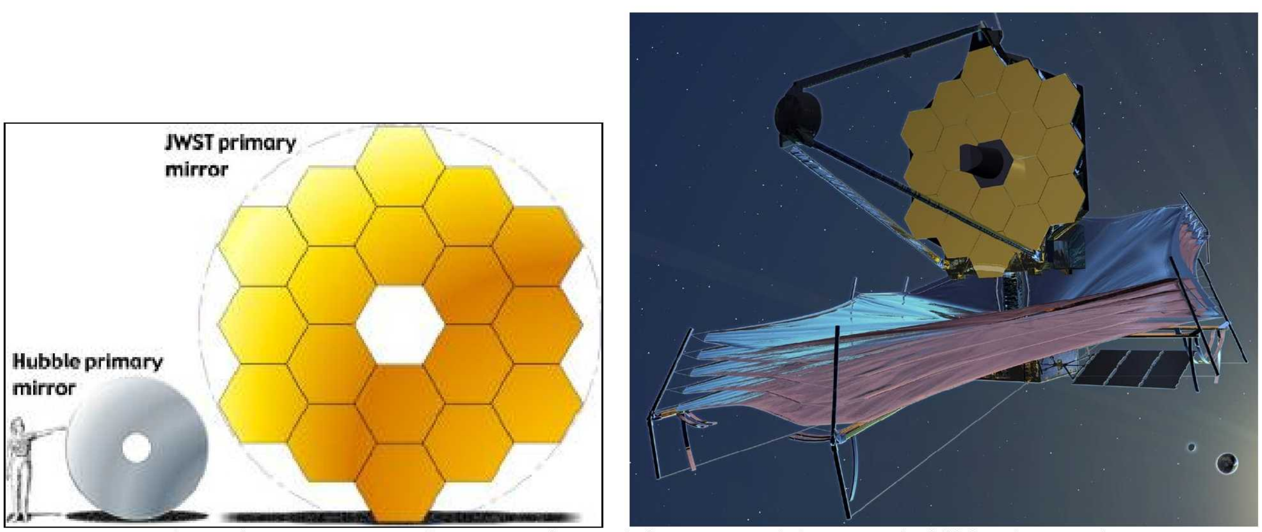

Figure 1 Hubble to JWST comparison—2.4 m versus 6.6 m- that's 22' in diameter!

ITT is the subcontractor responsible, through NGAS, for the JWST system integration and system level optical testing. The integration of the telescope optics onto the composite telescope structure occurs at the Space System Development and Integration Facility (SSDIF) at NASA GSFC. All of the GSE discussed in this paper have undergone a Critical Design Audit in March 2009 and final design details and procurement are underway.

Unlike many telescope systems, the adjustable nature of the JWST means that the initial installation of the adjustable optical components (PMSAs and SMA) does not require tight optical tolerances to achieve the specified alignment required to meet optical performance requirements. The active primary mirror segments and adjustable secondary mirror (all with six degrees of freedom actuation capabilities) allow the system to be fine aligned to optical tolerances on orbit by wavefront sensing and control[4] rather than by a precision ground alignment. As a result, integration of the adjustable optics are determined by mechanical placement tolerances on the order of 500 µm and 500 µrad. These tolerances are derived primarily from the actuator range budgets to ensure adequate range of motion of the adjustable optics on orbit. Nonetheless, these integrations are challenging from many perspectives. With eighteen 1.32 m segments and a 6.6 m PMBA, the scale of the integration is immense. Reach and access, placement verification over such a large volume, and the sheer size of the structure presents its own challenges. When viewed in comparison to the Hubble primary mirror, Figure 1, the JWST is simply massive. Development of a process that can efficiently integrate 18 segments is essential to program success. The Primary Mirror Alignment and Integration Fixture, developed by ITT, is used to integrate all segments with a single piece of GSE.

The wavefront sensing and control process aligns the PMSAs and SMA to the Aft Optics Subsystem on orbit. The fixed optical elements (tertiary mirror and fine steering mirror) contained within the Aft Optics Subsystem require tighter integration tolerances because they essentially define the telescope optical axis. The tolerances for integration of the AOS are less than 200 µm and 200 µrad. The AOS, weighing in at over 400 pounds and measuring 1.1 m x 2.1 m, presents unique integration challenges with respect to alignment adjustability during integration. To overcome this, surrogate GSE matched to the AOS will be used to determine the rigid body alignment of the AOS before integration of the AOS structure.

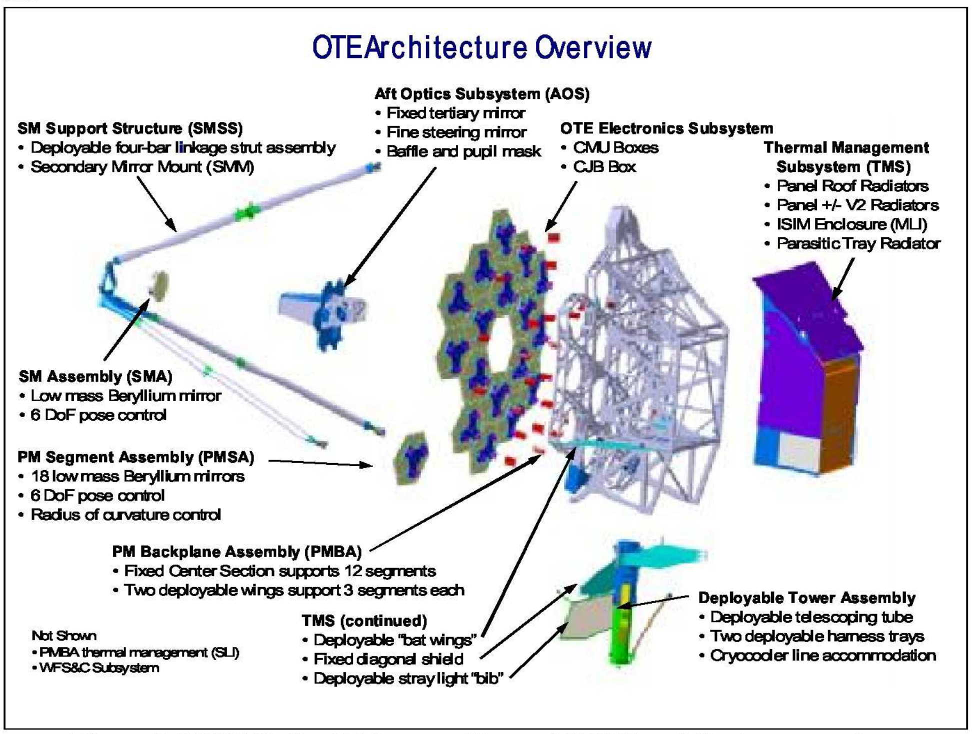

Figure 2 JWST Optical Telescope Element (OTE) architecture overview.

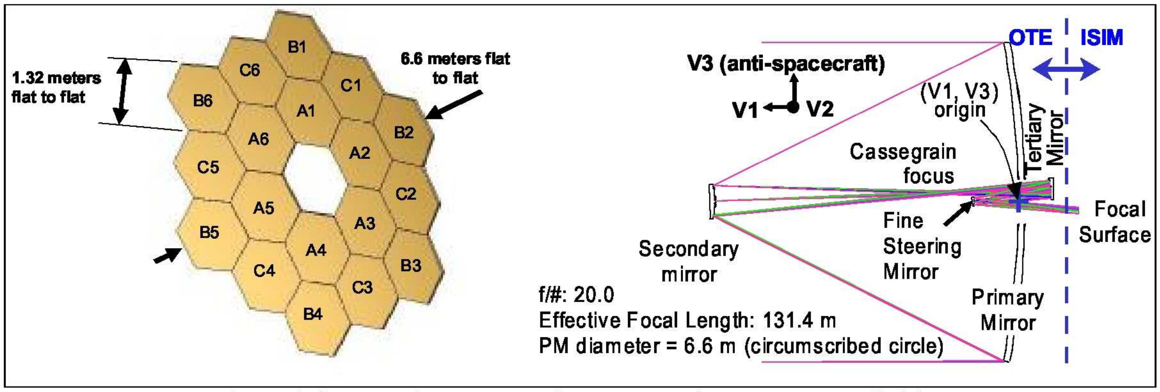

Figure 3 OTE optical schematic and coordinate system definition

2. INTEGRATION COORDINATE SYSTEM

The Primary Mirror Backplane Assembly (PMBA) integration occurs at ATK and Northrop Grumman Aerospace Systems. The 3 interfaces to the Aft Optics Subsystem, located in the center hex of the PMBA, define the PMBA coordinate system. The three interfaces, illustrated in Figure 4 and Figure 5, define the M1, M2, M3 coordinate system. The nominal telescope coordinate system, V1, V2, V3, is parallel to the M coordinate system and has its virtual center on the vertex of the ideally aligned primary mirror. All optics placement requirements are with respect to the M coordinate system.

The choice of a set of integration master references for telescope integration is critical to achieving a workable and efficient alignment process, and there are many considerations involved. Line of sight access, gravity sag susceptibility, thermal stability and ease of reach and access are factors for the choice of integration master references. A coordinate system should be chosen which limits the number of required coordinate transfers Limiting the coordinate transfers will increase the effective actuator range of the adjustable components.

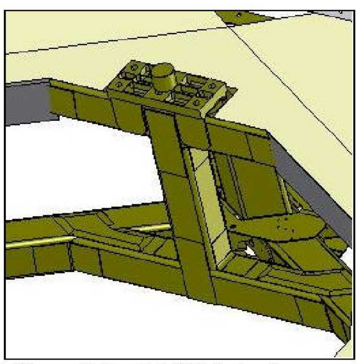

Figure 4 One of the 3AOS interface on PMBA

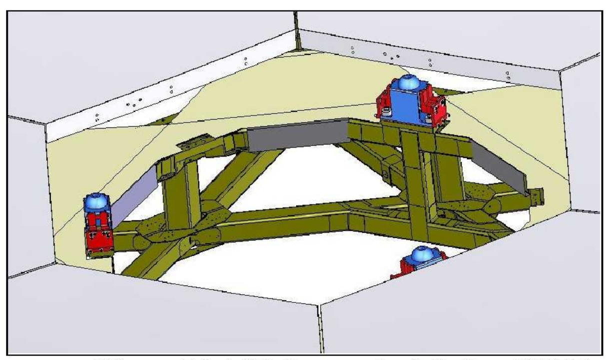

Figure 5 3 AOS flexures installed on PMBA

The Aft Optics Subsystem, as the only fixed component, is the logical choice for an integration coordinate system. Aligning the PMSAs to this coordinate system would maximize PMSA actuator range. Integrating all optics to references on the as-built, as-integrated AOS, would eliminate some required coordinate transfers, thereby minimizing noise in the process. Unfortunately, the Aft Optics Subsystem delivery schedule precludes its use as the coordinate system during PMSA integration. However, the AOS interface can still be used as integration reference through the use of the AOS Master Alignment Fixture.

The AOS Master Alignment Fixture (AMAF) is used as an AOS surrogate to align the AOS interfaces during AOS component assembly and alignment at Ball Aerospace and Technologies Corporation (BATC). The AOS mounts to the PMBSS via 3 spherical ball and cup interfaces as illustrated in Figure 6. The cups on the AOS side of the interface are matched to cups on the AMAF during AOS assembly at BATC.

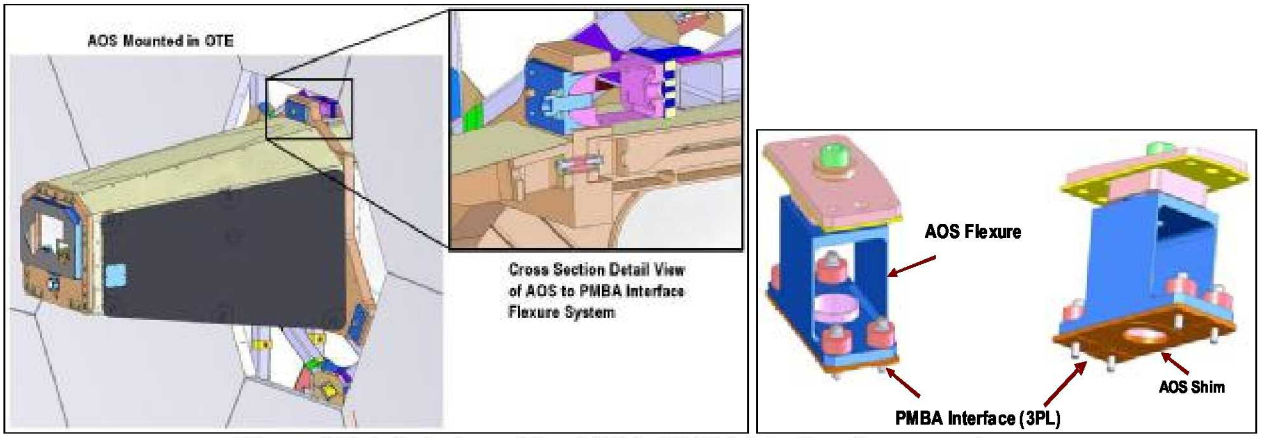

Figure 6 Detailed view of the AOS to PMBA interface flexure system.

The AMAF, illustrated in Figure 7, is the OTE master coordinate system for integration of all optical elements. As the master coordinate system for integration, the AMAF is integrated first. Seven locations on both the top and the bottom of the AMAF are used for mounting opto-mechanical targets such as a laser tracker targets or precision tooling balls. These locations are illustrated as spheres in Figure 7.

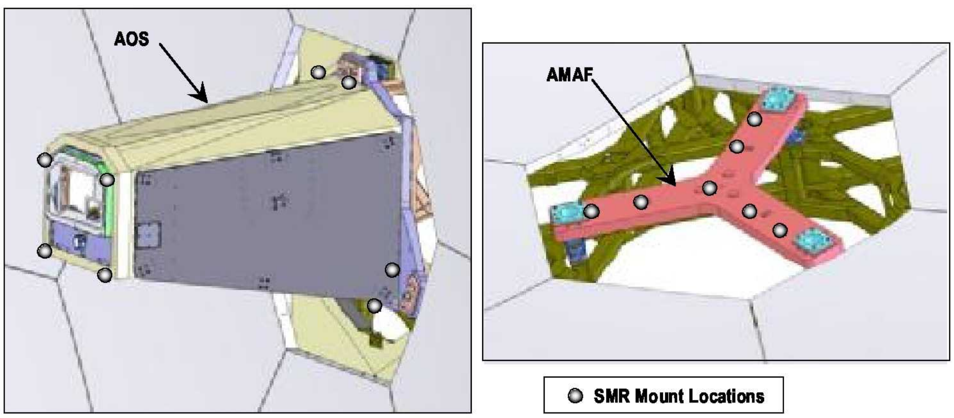

Figure 7 Illustration of AOS and AMAF mounted on the PMBSS.

3. METROLOGY TARGET DESIGN

A variety of references are required for OTE structure integration, OTE optical alignment, JWST Observatory integration, JWST Observatory testing and integration to the launch vehicle. The references discussed in the section are developed collaboratively with the JWST team.

Precision mechanical features for opto-mechanical references are machined into the side of each PMSA and SMA. This is a unique feature of a telescope composed of Beryllium optics in which references can be directly machined into the optical components. The PMSAs have 3 locations on each of the 6 sides of the mirror as illustrated in Figure 12 and Figure 14. Each location consists of a quarter inch diameter precision bored hole with countersunk threads for screwing in metrology references. Adjacent to each of these locations is a precision bored hole to create an accurate clocking reference. Three spherically mounted retroreflector's (SMRs) are mounted on a precision block at each of the 3 locations preventing the need to rotate an SMR for line of sight to different trackers. A series of machined precision features on the AOS structure (spheres in Figure 7) are used for placement verification.

On a structure as large as the PMBA (occupying a volume of ~ 6.5 m x 6.5 m x 4 m), metrology references are required to verify gravity sag during the integration process and to serve as transfer references for integration of multiple laser trackers into a single measurement system. Tooling balls or SMRs are mounted to a series of bonded washers on the flight composite structure. A pair of bonded washers is illustrated in Figure 8 : one has a magnetically integrated tooling ball while the other tooling ball is sitting to the side . Testing of the samples demonstrated a placement repeatability of better than 12.5 μm.

The following references, see Figure 9, are located on the flight PMBA

1. Bonded washers located on the minus V1 side of each of the 54 (18 X 3) PMSA/PMBSS interfaces.
    a. Used as transfer references and for gravity sag verification.
2. 6 bonded washers along the wing to center section hinge line.
    a. used as a secondary reference system during Observatory testing
3. Bonded washers located on the minus V1 side of the AOS interfaces.
    a. Used as transfer references during AOS integration and verification and for gravity sag verification.
4. Bonded washers located within the backplane support fixture (not illustrated)
    a. Used as transfer references during AOS integration and verification
5. A series of 4 modular interfaces on the minus V1 side of the PMBA referred to as the OTE master references (OTE MR).
    a. These references are visible during the entire Observatory integration and test process

Figure 8 Picture of 2 bonded washers- one with a magnetic reference attached

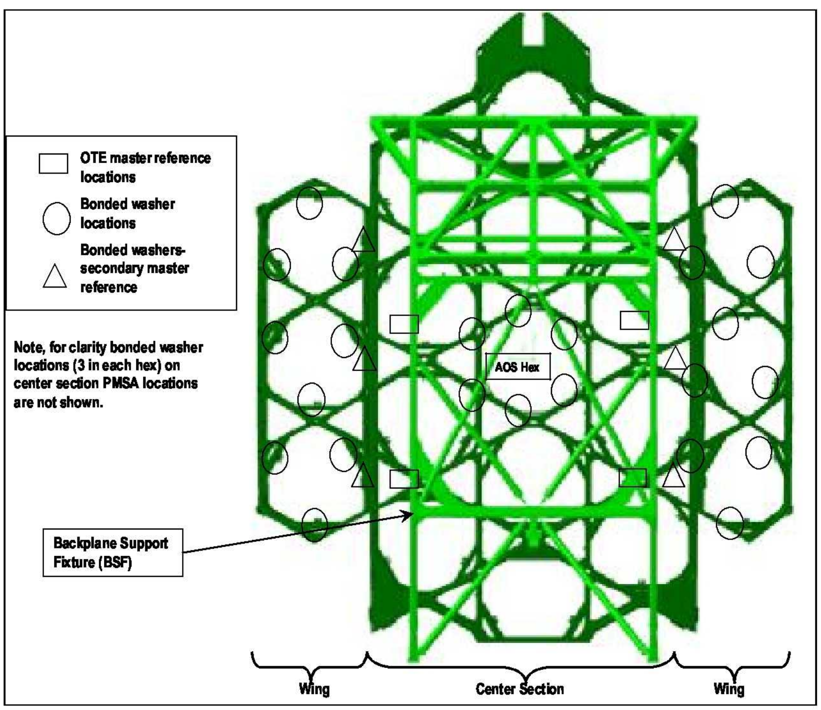

Figure 9 Illustration of metrology locations on the PMBA.

Each of the 4 OTE master references (OTE MR), Figure 10, consist of a napkin fitting with a modular interface for mounting metrology features (SMR, cubes, photogrammetry targets or tooling balls) via an interface plate. The OTE Master Reference locations were chosen for their insensitivity to gravity sag, the ability to view them during late stages of integration and for reach and access concerns when the telescope was being integrated in a primary mirror down configuration as discussed in reference [2].

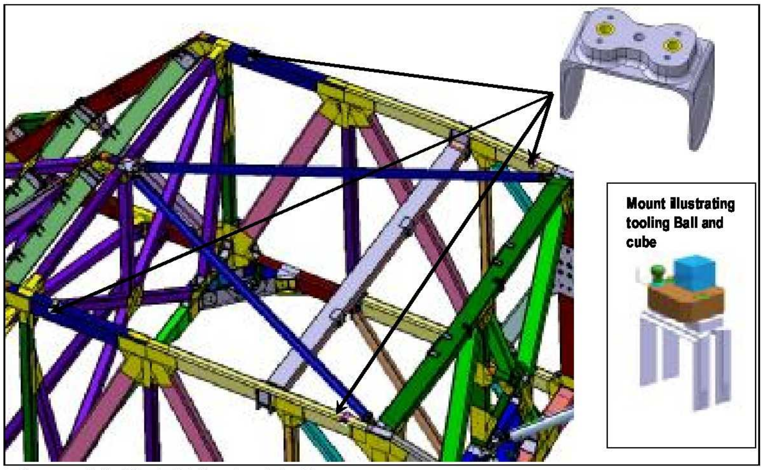

Figure 10 OTE Master References

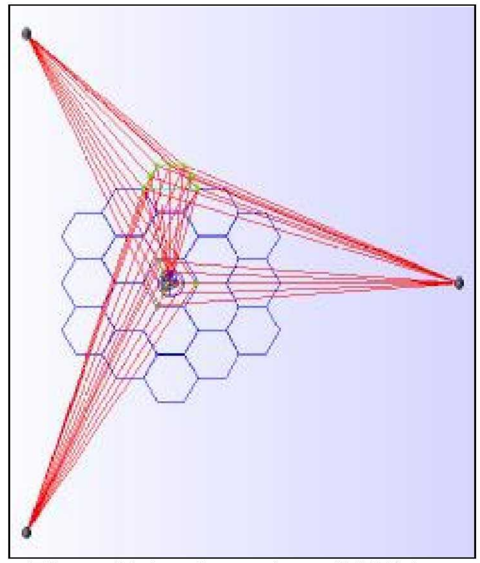

Figure 11 top down view of PMSA placement verification using 3 laser trackers

4. METROLOGY SYSTEM

Laser trackers and spherically mounted retroreflector (SMR) targets, Figure 12, mounted on flight hardware are used to verify the location of all optical components in a coordinate system defined by the AMAF. Figure 11 illustrates a top-down view of 3 laser trackers verifying the placement of one PMSA. Each of the red lines represent a measurement from one of the 3 laser trackers to an SMR. The laser trackers are mounted on 10 m tall metrology stands which are moved to different locations to ensure line of sight. Figure 14 illustrates the laser trackers in the SSDIF configuration as well as the SMR attachment bracket on the PMSA edges.

At the measurement distances in this arrangement, laser trackers are more accurate in their distance measurement than their angular measurement. To enhance system accuracy, the 3 laser trackers are united into a single measurement network using the Spatial Analyzer (SA) software provided by New River Kinematics which bundles the measurements to reduce noise by applying weights in a least-squares solution space.

Modeling of the placement uncertainty of an edge PMSA using the USMN feature in Spatial Analyzer results in a 2 sigma measurement uncertainty of each PMSA SMR target (before averaging) of less then 75 μm in decenter and piston and 45 microradians of tilt in a coordinate system defined by the AMAF. This is a small percentage of the total placement requirement of 500 μm and 500 μrad and easily fits the metrology allocation.

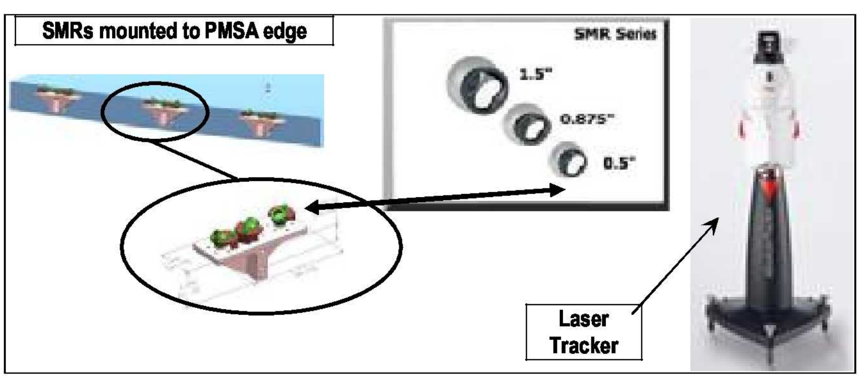

Figure 12 SMRs mounted to PMSA edge, and the recently released Leica Absolute Tracker

5. INTEGRATION GROUND SUPPORT EQUIPMENT (GSE)

The integration activities occur using an integrated system of Ground Support Equipment illustrated in different use configurations in Figure 14, Figure 14, Figure 16, Figure 22 and Figure 26. The OTE is supported by a system of (6) hardpoint struts that connect to a large support structure referred to as the Optical Bench. The Optical Bench is a sub-assembly of the Ambient OTE Assembly Stand (AOAS) that also includes the Personnel Access Platform Structure (PAPS). The PAPS provides assembly personnel access to both the +V1 and –V1 sides of the OTE. It includes both deployable and rolling work platforms that facilitate reach and access to locations as illustrated in Figure 16. The AOAS also serves as the structural support for the two Sub-Assemblies that are used for PMSA positioning during integration. The Optics Integration Gantry System (OIGS) is a bridge crane system that spans the Primary Mirror and supports the PMSA Alignment and Installation Fixture (PAIF).

The development of a single piece of GSE to integrate the 18 segments was challenging given all the limitations, constraints, reach and access concerns. The PAIF is a complex positioning system that supports each PMSA as it is placed onto the PMBA and adjust its alignment based on the laser tracker measurements. It adjusts in clocking angle, T_4, to attach to any of the 6 sides of any of the 18 PMSAs and adjusts in tilt, T, to match the 3 different PMSA prescriptions. With a coarse vertical translation stage for gross movements, and a micro positioning hexapod for final alignment, the PAIF contains all degrees of freedom to integrate all 18 segments using a single piece of hardware.

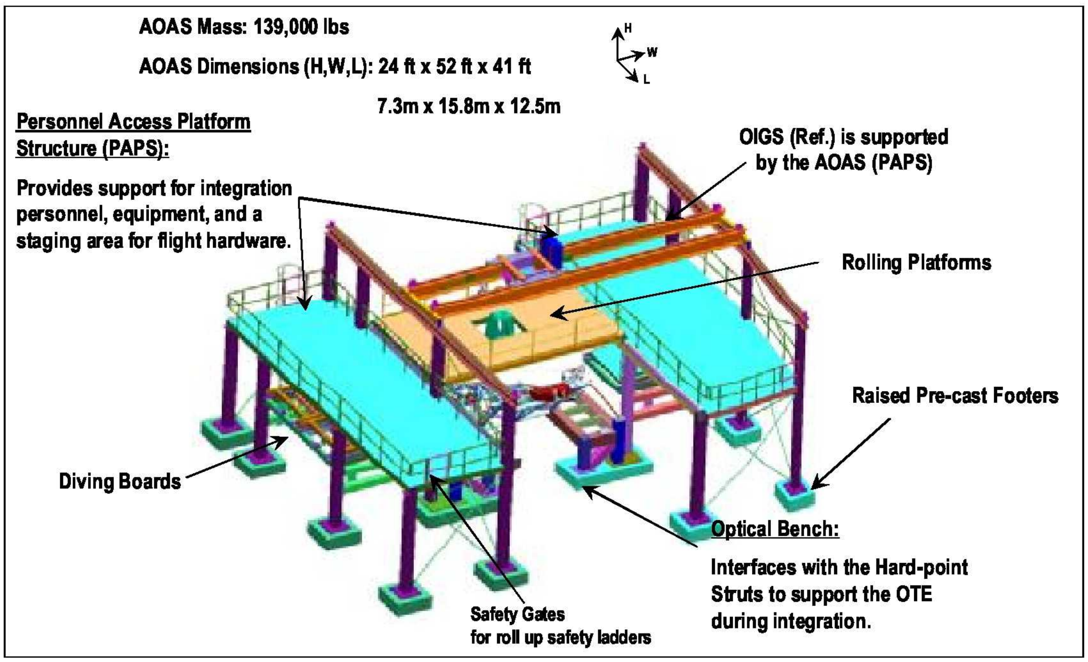

Figure 13 Ambient Optical Assembly Stand Overview

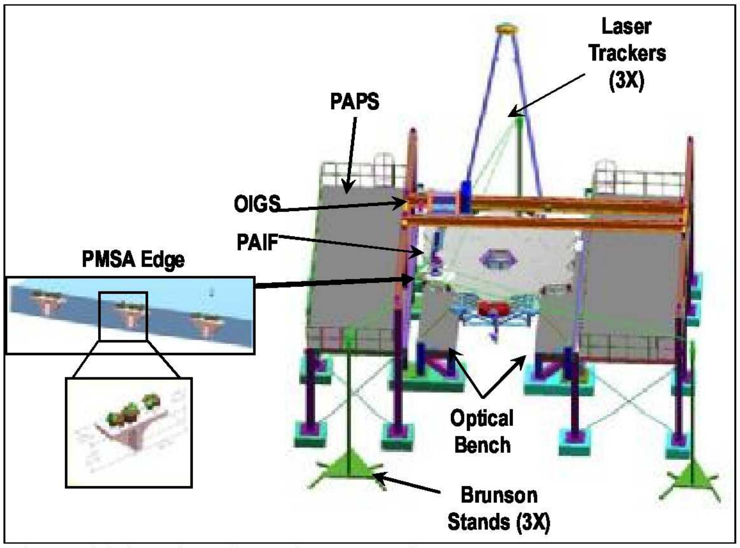

Figure 14 Ambient OTE Assembly Stand configuration illustrating laser tracker usage and SMR cubes mounted to the side of a PMSA

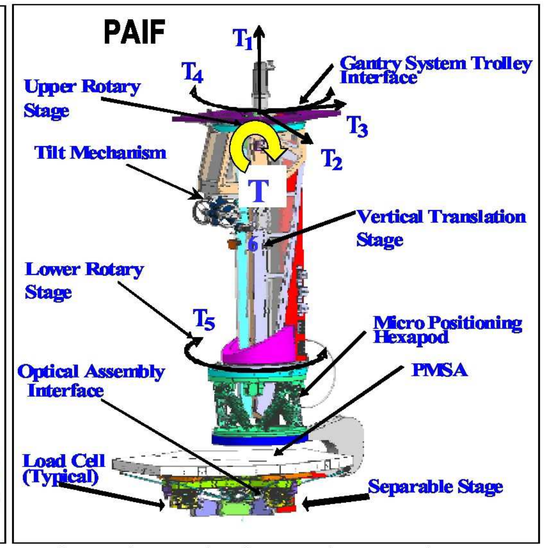

Figure 15 detail of the Primary Mirror Alignment and Integration Fixture (PAIF)

Figure 16 – AOAS illustrations, deployable platforms for reach and access, PAIF holding PMSA and PAIF prior to PMSA integration.

6. OPTICAL TELESCOPE ELEMENT (OTE) INTEGRATION FLOW

Figure 17 details the top level integration flow for OTE optics integration and will be described in more detail in the following sections. Once the Primary Mirror Backplane Assembly is installed, a metrology scan of all flight interfaces, bonded washers, OTE Master Reference (OTE MR), and other structural references is conducted using laser trackers. During this process, the M coordinate system is transferred to other references so that the AMAF can be installed (the AMAF covers up the references that define the M coordinate system). A cross check of the gravity sag of the telescope and any necessary updates to the structural model are performed. This gravity sag cross check occurs periodically during the integration process to ensure structural model accuracy. Integration of the 18 primary mirror segment assemblies, the secondary mirror and the aft optic subsystem follow. Once completed, the OTE moves onto ISIM integration and Observatory test.

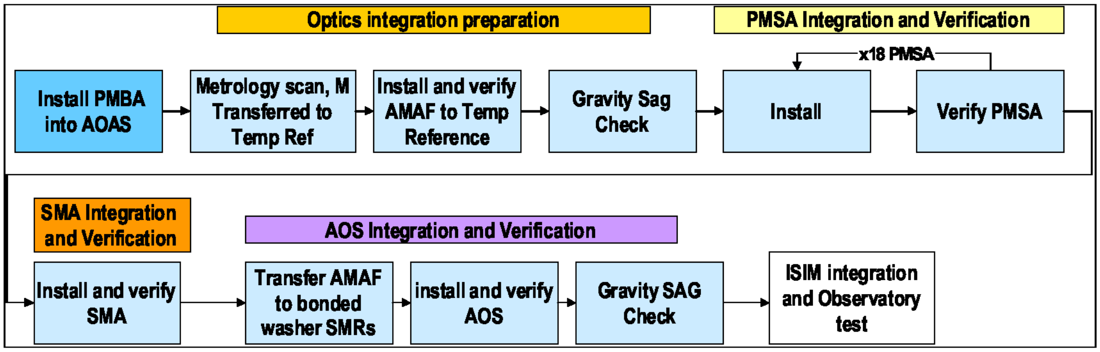

Figure 17 OTE integration flow

7. AOS MASTER ALIGNMENT FIXTURE (AMAF)INTEGRATION AND VERIFICATION

Before any flight optics are integrated, the AMAF is installed on the PMBA interfaces that define the M coordinate system using the process defined in Figure 18. The AMAF is used to align and verify the location of the the AOS flexures (including a shim if required) and defines the rigid body alignment of the AOS.

The M coordinate system is transferred to SMRs attached to bonded washers via laser tracker measurements and the AMAF is verified to this transferred reference. The AOS flexures are installed and aligned using the AMAF. The flexures and the AMAF are moved as a unit to align the AMAF in decenter and clocking and the AMAF is shimmed as required to meet its tip, tilt and piston placement tolerances using feedback from laser tracker measurements. The as-integrated AMAF now represents where the AOS will be installed and defines the coordinate system for all subsequent integrations.

By using the as-assembled AMAF as the coordinate system for integration, any errors in the transfer of the M coordinate system to the AMAF is eliminated from the PMSA, SMA and AOS placement error budgets because all of them are aligned to a common coordinate system. This process reduces the errors in the actuator range budget.

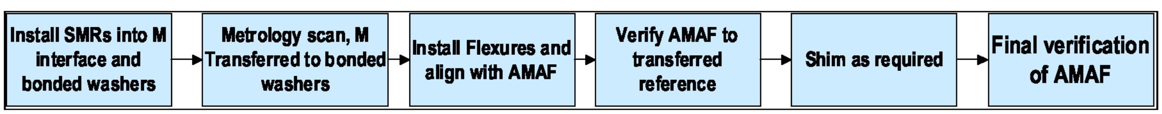

Figure 18 AMAF integration and verification process

8. PRIMARY MIRROR SEGMENT ASSEMLY (PMSA) INTEGRATION AND VERIFICATION

The placement requirements for the integration of the Primary Mirror segments with the PMBSS are determined by mechanical tolerances on the order of 500 µm and 500 microradians. Pre-determined mechanical shims are used to compensate for manufacturing errors on both sides of the PMSA/PMBA interface with respect to tip tilt and piston of each PMSA. The shims are determined by separately measuring the interfaces on the PMSA and PMBA. The PMBA interfaces are measured using laser trackers in a coordinate system defined by the AMAF. The PMSA interfaces are measured using a coordinate measurement machine (CMM) in a coordinate system defined by Mirror Master Reference (MMR) datums. These datums reference the optical surface during component manufacturing and test at BATC. Any errors in the PMSA shim prescription co-planarity are compensated by a liquid shim during PMSA integration.

Figure 19 details the PMSA installation flow and Figure 20 illustrates the PMSA/PMBA interface. Once removed from the shipping container, a CMM is used to determine the PMSA shim prescription. With the shims installed, the PMSA is loaded onto the PAIF as illustrated in Figure 16. The PMSA Alignment and Installation Fixture (PAIF) provides integration and test personnel the ability to adjust decenter and clocking alignment of each PMSA via a micro positioning hexapod illustrated in Figure 15. Laser trackers assist in the placement of the optics by providing placement feedback to integration personnel. All mirror moves accomplish with the PAIF are visually inspected by integration personnel to ensure hardware safety.

Figure 19 PMSA installation flow

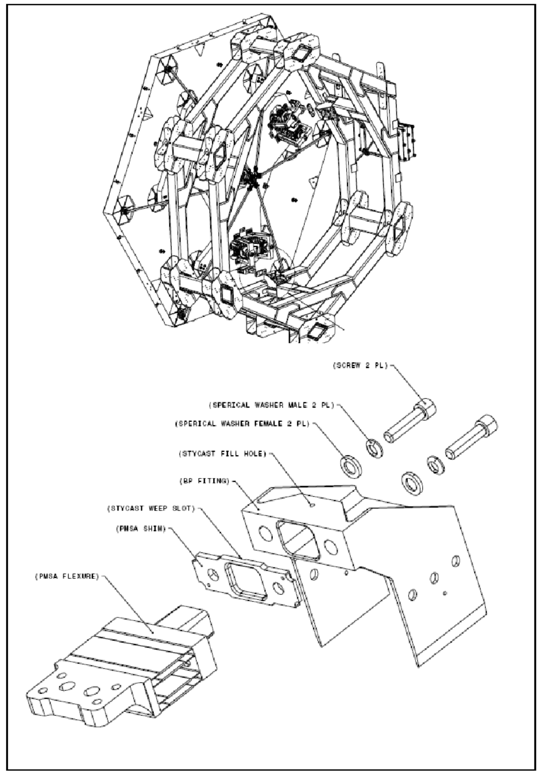

Figure 20 PMSA-PMBA interface detail and PMSA flexure to PMBA fitting detail

Once placed within tolerance, the interface is bolted, the PAIF is removed and final alignment verification occurs. This involves both verifying the PMSA location as well as verifying the gaps between PMSAs. After final verification, the PMSA interface is potted. Other steps include electrical harnessing, actuator testing and installation of the thermal and optical closeout.

Alignment Verification requires precise accounting of system level biases and coordinate system transfers. The bias due to the gravity sag of the telescope structure is calculated through analysis of the structural model and is cross checked by measurements of SMRs attached to the telescope structure via bonded washers. Figure 21 illustrates a simplified flowchart of this process.

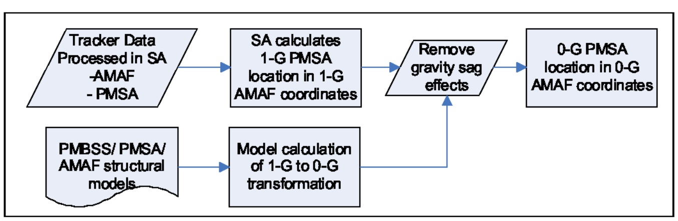

Figure 21 Process for predicting 0-G PMSA location

9. SECONDARY MIRROR ASSEMBLY (SMA) INTEGRATION AND VERIFICATION

With the Secondary Mirror Support Structure (SMSS) fully deployed, the height of the secondary mirror above the SSDIF floor would be greater than 15 m. Significant structure is required to support personnel and tooling to perform integration at that height so the secondary mirror is integrated with the SMSS stowed as illustrated in Figure 22. The Secondary Mirror Alignment and Integration Fixture (SAIF), Figure 23 and Figure 24, is located on an assembly stand adjacent to the AOAS. The SAIF supports the secondary mirror and has a translation assembly with X, Y and Z translations as well as clocking around the central support post. Fine tip and tilt of the secondary mirror is accomplished by manual adjustment of the SMA Alignment Gimbal.

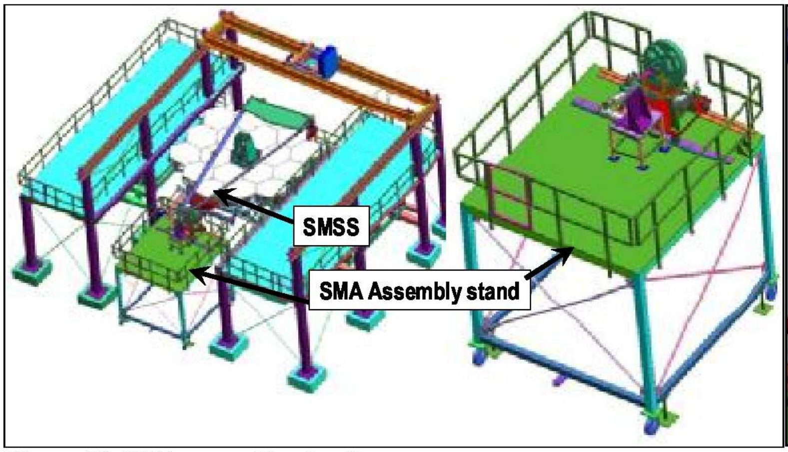

Figure 22 SMA assembly stand

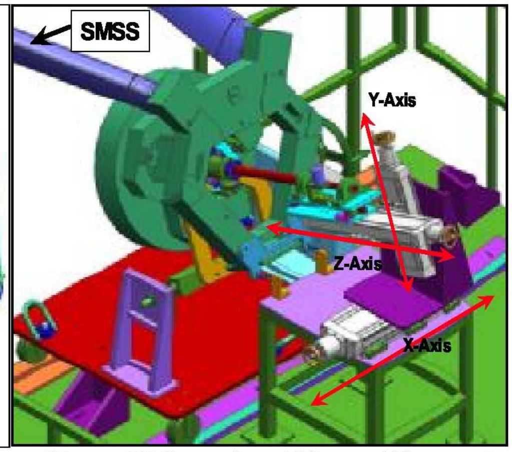

Figure 23 Secondary Mirror Alignment and Integration Fixture (SAIF)

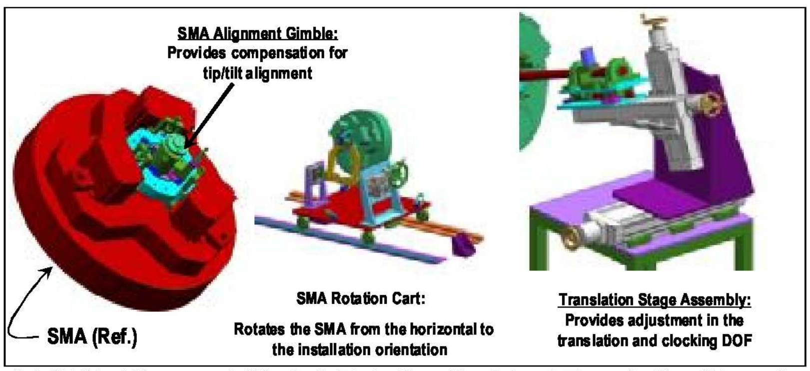

Figure 24 SMA Alignment Gimbal, Rotation Cart And Translation Stage Assembly

With the SMSS deployed, laser trackers measure the alignment of the SMA interfaces on the SMSS with respect to the AMAF. This determines the SMSS component of the shim prescription. The SMA is measured with a CMM to determine its interface alignment with respect to the SMA MMRs. These two measurements determine the shim prescription for the secondary mirror. The laser tracker is also used to measure temporary references on the SMSS. These locations provide a transfer reference for placement verification.

Secondary mirror integration follows a similar process as the PMSA integration. The SMA Alignment Gimbal and the Translation Stage Assembly are used to fine align the SMA to the SMSS in decenter and clocking. Laser trackers are used to verify the placement of the SMA with respect to references on the SMSS.

10. AFT-OPTIC SUBSYSTEM (AOS) INTEGRATION AND VERIFICATION

The critical operations for AOS placement are accomplished during AMAF integration. By aligning the AOS flexures, the AMAF defines the rigid body location of the AOS, and any shimming for tip tilt and piston, decenter and clocking of the AOS are made during AMAF integration. The AOS integration process involves the removal of the AMAF and installation of the AOS using laser trackers for final verification.

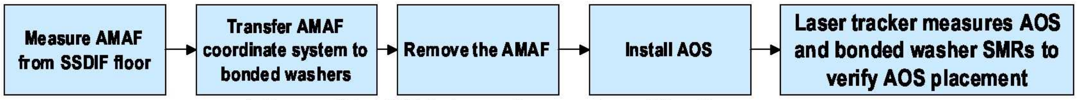

Figure 25 AOS integration and verification process

Figure 26 illustrates the AOS being lowered into place. The rolling platforms provide reach and access directly over the primary mirror and limit contamination.

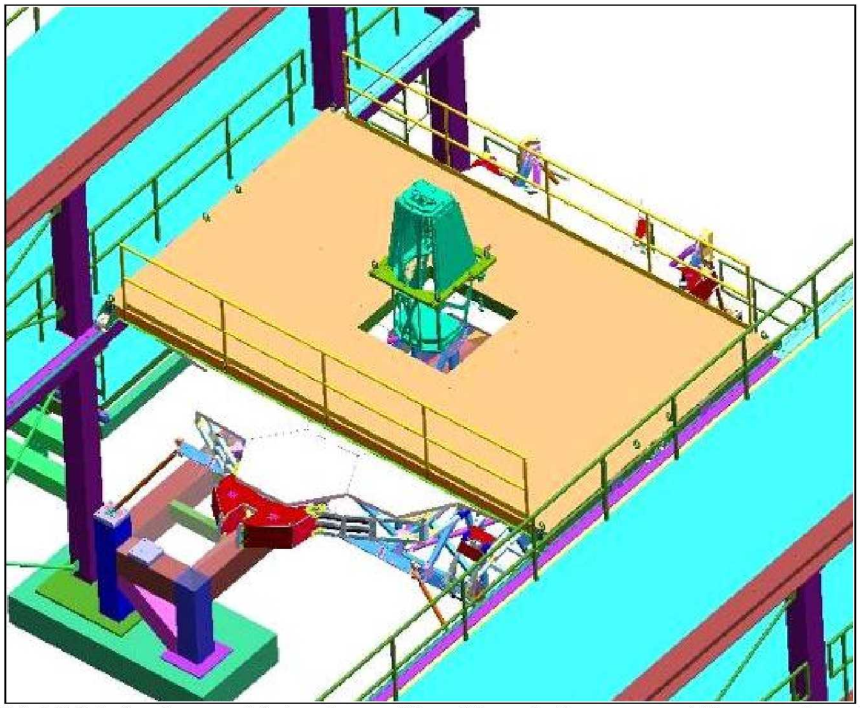

Figure 26 AOS being lowered into place with rolling platforms providing reach and access

11. CONCLUSION

ITT has developed a suite of ground support equipment to enable the efficient integration of the Optical Telescope Element. Critical to this process was the collaborative effort to develop a series of references on the flight hardware for optics placement verification. The use of the AOS Master Alignment Fixture as the integration master reference creates a logical and efficient coordinate system for integration and creates a simplified process for AOS integration. The Ambient Optical Assembly Stand enables the reach and access for the critical integrations. The PMSAs are aligned by a single piece of GSE, the Primary Mirror Alignment and Integration Fixture. A unified network of laser trackers ensure placement accuracy.

All of the hardware discussed in this paper have passed a Critical Design Audit in early 2009 and ITT looks forward to the integration process.

ACKNOWLEDGEMENTS

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